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Non-intrusive electric power monitoring system in multi-purpose educational buildings

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ABSTRACT

Understanding the consumption patterns in a working space is important for evaluating the causes of energy wastage and for developing strategies towards specific energy reduction methods. The intent of metering systems in buildings is to provide adequate data that help improve building systems performance. The results of the analysis offer the potential to improve the energy efficiency of the building and reduce the operation costs. Researchers of Polytechnic University of Madrid and American University of Ras Al Khaimah have developed a metering and control system that processes and analyzes the digitalized signals. This system can collect, analyze and manage the electrical consumption in buildings. It is non-intrusive, can be easily deployed in electric boards and sends data to a central base station located away from the metering device. In this article the system is tested in an educational facility with a wide range of uses. The lighting fixtures, power outlets and HVAC devices are analyzed in offices, classrooms and architecture studios. This article concludes that energy audits for longer time periods help building managers understand device profiles, occupant behavior and environmental context.

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1. INTRODUCTION

Energy consumption in non-domestic buildings includes different activities such as lecture halls, laboratories, offices or classrooms. The diversity of load types and requirements, energy consumption schedules and habits of users require appropriate equipment. Power monitoring systems components that use a disparity of protocols will be unable to exchange information. The heating, ventilation, and air conditioning (HVAC), domestic hot water (DHW) and lighting are examples of the systems involved. HVAC has been regarded as the three major factor influencing energy consumption in buildings over the last few years. Recent studies reveal that miscellaneous electric loads constitute the large majority of office equipment, while an important part of them is about plug loads related to Information and Communication Technologies (ICT), such as desktops, monitors, printers etc. The rapid market penetration of electronic devices has expanded this category significantly [1]. The U.S. Green Building Council estimates that buildings use 20% more energy on average than necessary due to obsolete equipment, design flaws and inappropriate use [2]. A variety of electronic devices also affect the power quality of the electric network, mainly by inserting harmonics in the voltage signal [3].

Using remote energy monitoring along with web-based technology allow owners to understand the building performance, take appropriate action, and continually improve energy efficiency [4]. In office, educational and commercial buildings the consumption patterns can vary dramatically among buildings of different types [1]. For example, office buildings exhibit high energy consumption from consumer electronics including PCs and monitors, while commercial buildings, such as supermarkets or malls, have significantly fewer consumer electronics, and significantly more energy consumption associated to HVAC systems and lighting [5].

In order to reduce the size and cost of mechanical systems an efficient building design approach is required. Many authors have demonstrated that design of zero-energy buildings induces both a net benefit in total energy demand and an increase of awareness for building owners. Up to 40% of electrical energy can be saved in buildings due to cost-effective energy efficient measures [6].

Passive measures have proven to be effective when it comes to energy savings [7]. Building designers are responsible of passive strategies, such as window orientation, high thermal insulation or efficient lighting fixtures. Increasing thermal insulation of buildings reduces the cooling and heating load by lowering heat gains or losses through the building’s envelope [8]. Replacing obsolete HVAC equipment and lighting fixtures will increase the efficiency of building energy production system [9]. Thermal insulation of exposed water distribution pipes helps lower heat losses. Shading devices in facades prevents solar radiation from entering the building and reduces cooling load and the greenhouse effect. High performance glass with low emissivity coatings can reduce heat losses in winter. Reflective coatings in windows may help reduce cooling loads in summer [10]. At last, studying the color of roofs and external walls can control the heat absorbed by the building´s envelope [11].

Active strategies can also be considered to accomplish energy improvements [12]. Active measures, such us programming operational schedules, installing thermostatic valves are more complicated to implement and it is necessary to involve building managers and owners in the decision making process. All active measures may be centralized in the Building Management System (BMS). The aim of a BMS is to assure that energy demand in the building is accomplished without compromising the air quality and comfort levels of occupants [13]. The BMS can collect measurements at a specified time interval at designated measurement points. The factors that influence the selection of a metering system are accuracy, ease of deployment, communication protocol, and cost. [14]. The measurement results are communicated to the system’s base station. Conducting power measurements in different building types will provide managers with relevant data about the operation of buildings and will help end-users reduce the energy consumed by electrical systems in their facilities [15]. Isolating specific building areas will allow building managers to set active measures, such as automatic scheduling or behavior programs for building staff [16]. Analyzing these data will help them take appropriate actions over the life-time cycle of the facility. Some authors have developed methods of measurements to provide a useful comparison of different building areas [17]. The potential for energy savings in non-residential buildings can be up to 29% [18]. The energy management policies and regulations and human factors are very important elements influencing building energy consumption [19]. Building managers can provide his clients with meaningful information and feedback on electricity consumption as a tool to understand the performance of buildings and ultimately save energy [20], [21]. Studies in scientific articles have evaluated that more than half of the total building energy is consumed during the non-working hours, often without the knowledge of the consumer [22]. Power monitoring system can be used for power management, power plant operation, billing information, event verification, and troubleshooting [23].

In this article the consumption of different circuits within an educational facility will be studied. A new measurement method developed by researchers of Polytechnic University of Madrid (Spain) and American University of Ras Al Khaimah (UAE) will be tested and finally the results will be discussed.

2. RESEARCH METHOD

In the first step, this section describes the metering system developed by the research team of Polytechnic University of Madrid. In the second step, the section shows the studied facility. It is a multipurpose building with offices, small classrooms, library, auditorium, cafeteria and halls for social gatherings. It is a three-floor building in compliance with Spanish Building Code (2007 edition). The area of the building is approximately 3.500 m2. The selected spaces have an average occupancy, a daily schedule and a variety of equipment required for operating architecture studies, classrooms and offices. Section 3 reports the field measurements of the electrical circuits. Energy consumption data was broken down between heating, ventilation and air conditioning (HVAC), miscellaneous office equipment and lighting. The consumption was also broken down between working hours (08:00–20:00 h) and non-working hours. The

period of data collection and analysis was February 1, 2014 through May 31, 2014. The facility was used 5 days a week (Monday to Friday), from 8:00 a.m. to 8:00 p.m.

2.1. Description of the metering system

The power consumption in buildings tends to grow in proportion to the increase in the number of large-sized electric appliances [24]. The understanding of patterns and habits of energy consumption are key requisites for saving energy in buildings [25]. Nowadays, equipment for device-level monitoring is available by using smart plugs, smart power outlets and smart power strips. Hardware products for energy metering in the main electric board are more stable and reliable, though their price is still high.

The UPM research team has designed and manufactured more sensitive meters to perform sub-metering in specific branches or circuits of the building. Measuring electric energy in sections allows the identification of higher consumption areas, the detection of abnormal conditions in voltage and current of the building.

The proposed metering system is made up of three components: a) microcontroller unit (MCU) with 12 different channels to measure the current consumption waveform b) open-core current clamps measuring single-phase and three-phase true Root-mean square (RMS) electric energy flow and c) a wireless device of data transfer to a central base station located remote to the location of the metering device. The MCU can be applied to individual circuits so that the building manager can identify all details of the energy consumption. For the in-building test, the wireless metering systems will be configured for 5-minute measurement time intervals. Further, each data-series record must be labeled with a time stamp. The interface displays the consumption of electric energy parameters and can be consulted via the Internet. Open protocol is used for data transmission and collection. The advantage of using an open protocol is the software can be configured to read data from monitoring devices made by different manufacturers. The metering system shall collect Watt-hour energy for a three-phase circuit. Such a meter could be applied to a whole-building, individual panel, or individual circuit within an electric panel. Further, each data-series record must be labeled with a time stamp. Measurement data will be collected by the base station for transfer to the connected computer. A data record for a specific time must include values for all measurements plus a time stamp and a field that identifies the specific metered device name. Values for all of these variables are required for a data record to be considered successfully received. The research team installed metering devices throughout the facility. Although this approach might be more expensive, it helps understand better both the energy usage and the quality of the energy. Installing high-end metering devices at the main electrical board provides engineers with the total amount of energy consumption, but installing devices at distribution boards may allow users and engineers to identify saving opportunities and electrical malfunctions that can damage the appliances.

2.2. Description of the facilities

The Polytechnic School of San Pablo University Campus in Madrid is a multi-function building with classrooms, offices, library, auditorium and restaurant. The measurements have been carried out to analyze the Senior Design Project studio, along with offices and small classrooms. The addition of power monitoring was a response to several issues related to inefficiency and wasting energy in the building. Power quality issues can cause equipment to be damaged. A large and important part of this project included the installation of power meters and circuit monitors to provide power-monitoring capabilities. The period of data collection and analysis was February 1, 2013 through May 31, 2013. The facility was used 5 days a week (Monday to Friday), from 8:00 a.m. to 9:00 p.m.

All the offices have an opening facing west and there is not a shading device protecting the window. The analyzed rooms require day lighting, ventilation and mechanical systems. The HVAC system comprises a Variable Refrigerant Volume (VRV) outdoor unit and several internal units on the same refrigerant loop. The measurements have been taken from the first floor electrical board to analyze the open office with five work stations connected to the power outlets placed on the walls. Figure 1 shows a schematic of the electrical board and the circuits allocated to lighting and power outlets. It describes the number of circuits and the light fixtures connected to them, along with the measurement system.

Prior to installation, the technical information of the building was studied to specify locations of electrical panels on which metering were installed for testing. Electrical panels are located in electrical closets throughout the facility.

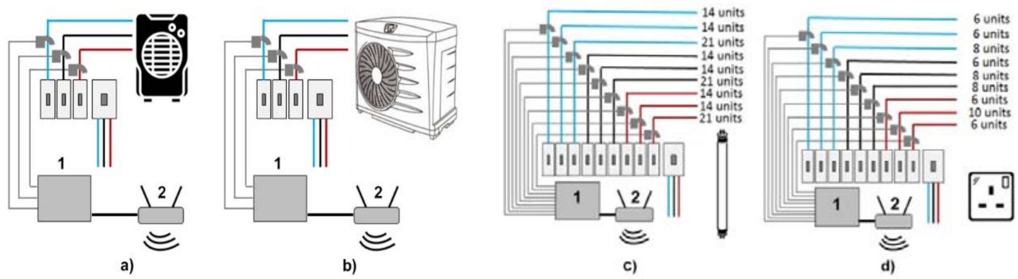

Figure 1. Diagrams of measurement devices. Architecture studio:
a) HVAC fan coil units, b) HVAC VRV units, c) fluorescent lamps, d) power outlets. Current clamps are connected to MCU unit (1). Data are transferred via wireless (2).

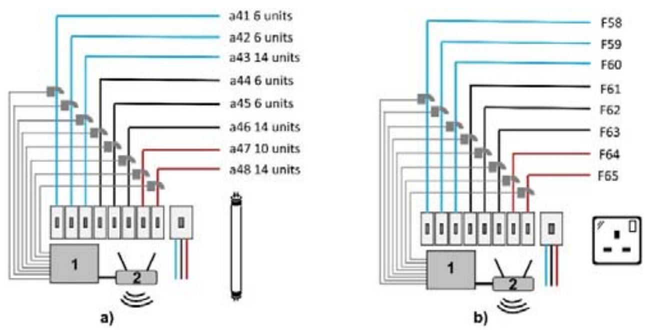

Figure 2. Diagrams of measurement devices. Offices and classrooms:
a) fluorescent lamps, b) power outlets. Current clamps are connected to MCU unit (1). Data are transferred via wireless (2).

3. RESULTS AND ANALYSIS

This section presents the analysis on the data for the Spring Semester of 2014. The measurements help understand the electrical energy consumption patterns. The current clamps receive the recorded data and the electrical energy consumption is then broken down in its HVAC, outlets and lighting components.

3.1. Analysis of the architecture studio

The lighting fixtures in the architecture studio are responsible for 58% of the classroom total energy consumed throughout the weeks. HVAC system, considering the chiller UE14 and the fan coil units, is responsible for 27% and finally, the outlets consumption represents 15%. Figure 2 shows the contribution of the three components to the total classroom load over the period of data collection.

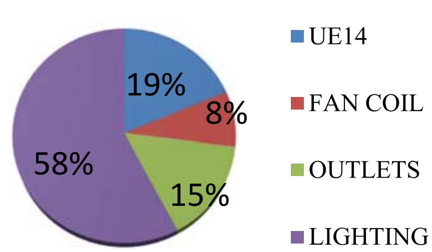

Figure 4. Energy consumption distribution architecture studio.

Table 1 shows the energy consumption in kWh of different energy sources over one week. As it was expected, the energy consumption over working days is higher than over the weekend. Based on the results we can infer that outlets have little impact on working days energy balance. However, the consumption is not reduced over the weekend. One reason for this is the energy required to keep the equipment (desktop computers, laptops, monitors and printers) in stand-by mode. The table also provides information on lighting and on the use of the HVAC system.

Table 1. Electrical energy of the Architecture studio (kWh)

Day	UE14 (kWh)	Fan-coil (kWh)	Outlets (kWh)	Lighting (kWh)
06/03/2014	32,75	13,69	24,67	118,61
07/03/2014	34,59	13,51	25,10	112,30
08/03/2014	9,78	6,30	19,38	11,47
09/03/2014	9,74	6,19	16,96	11,47
10/03/2014	60,77	14,72	23,56	112,03
11/03/2014	40,81	14,48	17,84	114,01

Figure 4 show that more than half of the electrical power is utilized for the purpose of providing light to the architecture studio, so the next step was to break down the daily consumption in eight different circuits to get to understand the power consumption patterns.

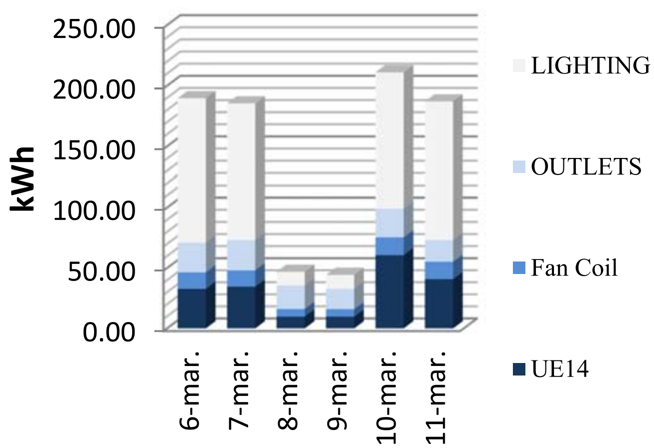

Figure 4. Energy consumption distribution over one week.

Figure 5 shows the consumption of individual lighting circuits. The daily consumption ranges between 700 and 1,300 Watts over the working hours. The power consumption is relatively stable. The vertical axis shows the Watts consumed for each individual circuit. The horizontal axis shows the time in hours. The system is working daily from 8:00 am to 9:00 pm. The power consumption of each circuit is different due to the number of lighting fixtures.

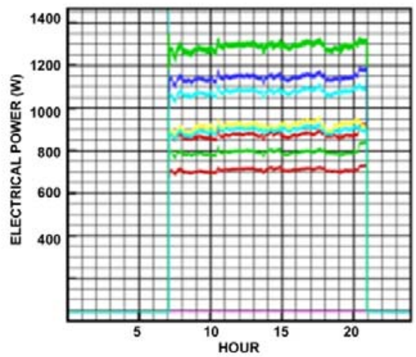

Figure 5. Power consumption of 8 lighting circuits on March the 6th, 2014. Architecture studio.

HVAC system plays an important role in the overall power consumption. A three-phase system is used in the HVAC system due to the heavy electrical power. Choosing a highly efficient system is key to lower the electricity costs and to reduce the environment impact. The electricity demand of the HVAC system is divided in two parts: the variable refrigerant flow (VRF) chiller and the fan coils. Figure 6a shows that electricity demand of the chiller rises up to almost 4,000 W when the system starts up.

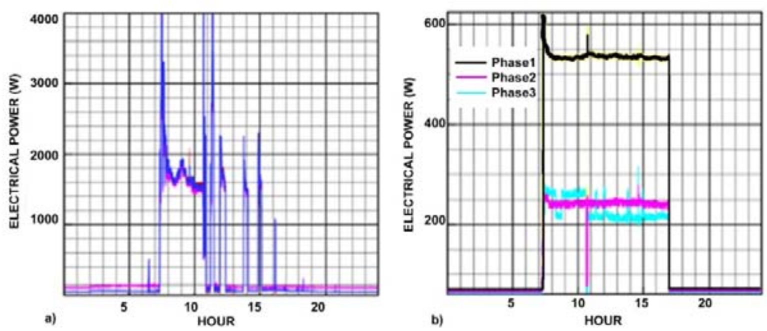

Figure 6. Power consumption of the HVAC system on March the 6th, 2014. Architecture studio, a) consumption of Variable Refrigerant Flow units, b) consumption of Fan-Coil units.

Then it remains steady for more than five hours when the indoor temperature reaches the comfort zone. The rest of working hours the chiller is on for small intervals of time. Therefore, the demand from 11:00 am to 9:00 pm is lower than the demand in the first three hours of the day. Figure 6b illustrates the electricity consumption of the fan coil units in the architecture studio. Energy consumption remains steady for nine hours. There is no relation between the working hours of the chiller and the fan coils. Three power measurements utilizing the current clamps show that the three-phase alternate current loads are not balanced in the Fan coil system. One of the phases consumes up to 550 W. This value remains steady for ten hours. Meanwhile, the other two phases consume 250 W. By definition, an unbalanced circuit has at least one phase current that is not equal to the other phase currents. In all cases, all three phase voltages are assumed to be equal and separated by 120º of rotation. The unbalance decreases the motor efficiency by causing extra heating and can cause faults in the motor, resulting in, tripping or permanent damage of the electrical equipment. Heat generated also affect the equipment life by increasing the operating temperature.

The power systems engineer is responsible for distributing these loads equally among the three-phases to maintain the demand for power fairly balanced at all times. The resultant power is higher than the ideal power when it comes to the electricity bill. Figure 7 shows the performance of the three-phase circuits of the VRF and fan-coil units over a week. The malfunction pattern is repeated every day in the fan-coil equipment because one of the phases is clearly unbalanced.

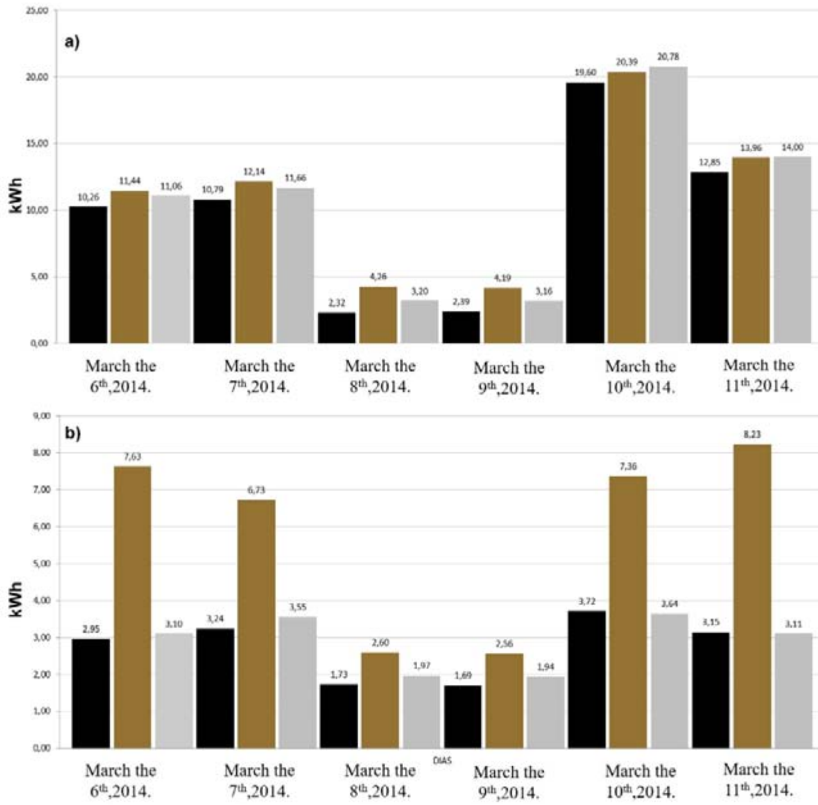

Figure 7. Power consumption of the HVAC system over a week. March 2014. Architecture studio, a) consumption of VRF units, b) consumption of Fan-Coil units.

3.2. Analysis of offices and classroms

Table 2 shows the daily electricity consumption of the offices over one week of the spring semester. The consumption is broken down into three categories: HVAC system, lighting circuit and power circuit with wall outlets. Weekend days (26/04/2014 day 3 and 27/04/2014 day 4) show a decrease in the electrical consumption. The lighting circuit represents the highest energy consumption percentage. This reveals a poor design of natural light. The electrical consumption of wall outlets remains steady over the weekend, although there were not any activities reported. That indicates that either the users did not switch off the devices when not in use or the standby mode consumption is not negligible. Finally, the HVAC system consumption decreased over the weekend because it is a centralized system controlled by the building manager. The stand-by mode might cause this residual energy consumption.

Table 2. Daily energy consumption in the offices.

Day	Lighting (kWh)	Outlets (kWh)	HVAC (kWh)
24/04/2014	63.90	32.76	34.35
25/04/2014	53.26	31.06	18.87
26/04/2014	29.76	27.58	7.43
27/04/2014	22.59	26.19	7.44
28/04/2014	49.79	30.68	35.35
29/04/2014	52.01	31.73	21.09

Figure 8 compares the daily electricity consumption of three systems over a week. Lighting and equipment connected to the outlets are responsible for more than 60% of the power required to run the offices. The next step was to analyze the daily consumption in different power and lighting circuits to get to understand the consumption patterns.

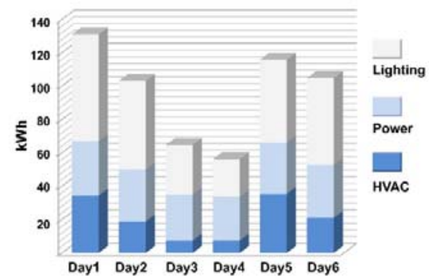

Figure 8. Energy consumption distribution over a week in offices.

After analyzing the overall electricity consumption over a week, the results show the daily consumption patterns. The measurement system allows to analyze each circuit so that the owner can understand the use of the equipment. Figure 9 shows the electrical consumption of eight different outlet circuits within the offices. Most of appliances cannot be switched off completely without being unplugged. These products draw power 24 hours a day, often without the knowledge of the consumer. We call this power consumption "standby power".The graphs show that the electricity used by appliances when they are not performing their primary function is relevant after working hours. Six out of eight circuits consume more than 100W over the night, so the steady consumption of outlet circuits over the weekend is due to the standby power.

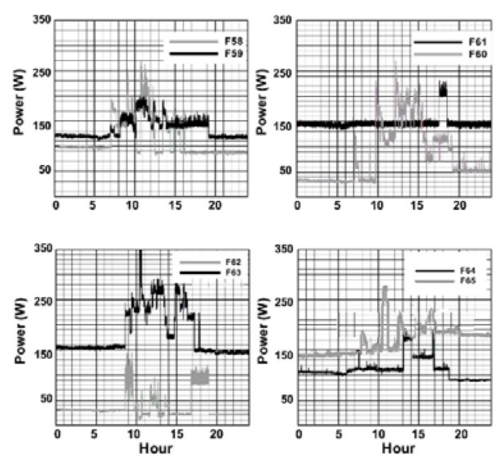

Figure 9. Power consumption of eight outlet circuits on the 24^{th} of April, 2014.

Figure 10 shows the electrical consumption of eight lighting circuits within the offices. The contribution of a46 and a48 circuits was at its peak for almost 10 hours a day. The system does not show data of occupancy and natural daylight design. Active measures such as deploying presence detectors to control the call for power can help reduce the lighting consumption. By replacing the light fixtures with more efficient models a considerable amount of waste energy can be saved. Most of the studied building lighting fixtures are fluorescent lamps. Light-emitting diodes (LEDs) can initially cost more than traditional lamps, but they will save energy and money over their lifetime.

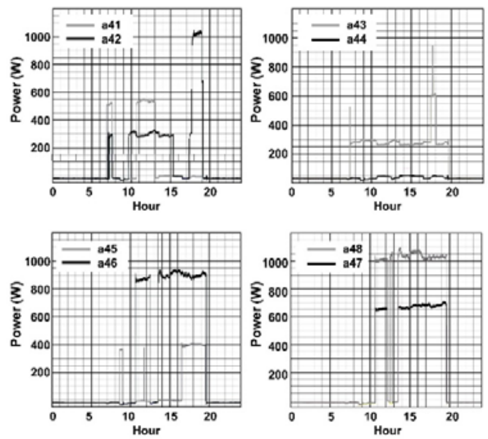

Figure 10. Power consumption of eight lighting circuits on the 24th of April, 2014.

4. CONCLUSION

An accurate metering can facilitate the development of strategies for reducing electric loads in buildings. A better knowledge of how energy is used within a facility allows owners to identify an array of prospects to improve efficiency, minimize waste, and reduce energy consumption. Assessment of data from the monitoring system can reveal existing issues that can adversely affect the operation of the electric appliances. The proposed system can provide information on voltage, current, power and waveforms. It is possible to have a significant impact on energy savings by analyzing the data. Lighting circuits make up almost 50% of electrical energy consumption within the analyzed spaces. The energy savings in lighting are mainly driven by the potential impact of active and passive measures. The former can be accomplished by deploying presence detectors to match occupancy and artificial light; the latter include the replacement of old lighting fixtures by more efficient ones. Automating some building operations towards energy savings, many involve both sensing and actuating. Sensing includes energy metering but also ambient context awareness such as occupancy and illumination in the offices. Actuating is about automatically switching off devices, or changing their mode of operation.

Standby power is responsible for more than 50% of energy consumption of electrical appliances, so there is a high potential of energy savings in the whole building. Electric devices can reduce the equipment's power usage by shortening the power saving delay time.

The behavior of the occupants affect significantly building consumption, so it is indispensable to engage building users and owners in energy-saving actions.

The proposed system observes the fitness of electric power to consumer devices, ensuring that the synchronization of the voltage frequency and phase allows electric systems to function without significant loss of performance or life.

Unbalanced operation of three-phase circuits can be detected with this system.

The obtained results showed the general usefulness of the developed tool. At the current development stage, further testing and validation with experimental data will be necessary to reach the next level of technological maturity.

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Fernando delAma Gonzalo, PhD, is an Assistant Professor of Architecture at Keene State College, NH, USA. He has seventeen years of teaching experience related to construction technology, building physics and energy management in buildings. He teaches courses in Building Construction and Architectural Design. He earned a Master in renewable energies at San Pablo CEU University in Madrid. Prior to that, he acquired more than 10 years of professional experience.
As a co-founder of a spin-off corporation, as an architectural bureau partner, and as a 3D graphic designer. He is a cofounder of IntelliGlass S.L., a technology based company, and has managed public research projects granted by the Ministry of Science and Technological Innovation and the Ministry of Industry, Energy and Tourism in Spain. As a result of these projects, he has published the patent document ‘‘Active Transparent or Translucent Enclosures with Energy Control Capacity’’ (PCT ES/2008/000071, USA 12/545510) as a co-inventor with other Spanish researchers.

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